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Influence of Nitrate Contamination on the Swell and Compressibility Characteristics of a Tropical Clayey Soil

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Abstract

This research work assessed the influence contaminated groundwater chemistry (especially nitrate contamination) on the volume change behavior during consolidation for a southwestern Nigerian clayey soil. 1-D Consolidation tests using deionized water and various concentrations of nitrate solution as the saturation/inundation liquid were performed on undisturbed clayey soil samples collected from Odi- Olowo Street (nitrate contamination prone area) in Akure, the capital of Ondo state, Nigeria. The compressibility/swell characteristics of the soil are influenced by nitrate contamination, as shown by the variation in the values of the coefficient of permeability, coefficient of consolidation, compression and swell indices (k, c_v, C_c and C_s). This implies that the swell potential, magnitude and rate of settlement are affected. These properties directly influence the performance of shallow structural foundations. It was concluded that lack of chemical analysis for soil and groundwater in a nitrate contamination prone area before construction could lead to an overestimation of the swell and compressibility indices for the site. Permeability of the clayey soil increased significantly with increase in nitrate contamination, this portends the danger of emerging breakthrough of contaminants in the shallow contaminated zone through the underlying clayey layer to deeper confined aquifers being relied upon for portable drinking water.

Keywords: Consolidation, nitrate contamination, permeability, pore fluid chemistry, regression models, swell characteristics

1. Introduction

A research into the compressibility behavior of clayey soil with contaminated groundwater in its pores is pertinent from an engineering and environmental stand point. Charbeneau, (2006) observed that groundwater quality may be impacted due to natural processes such as, run off from agricultural and urban watersheds, waste disposal practices and accidental spills and leaks. According to (DERM) 2009, leachate has the potential to damage soil structure. The high salinity of some leachate has tended to cause problems such as high concentrations of sodium and calcium ions that can alter soil structure through ion-exchange reactions with clay minerals. Leaching of natural chemical deposits can result in increased concentrations of chlorides, sulphates, nitrates, iron and other chemicals. The stress–strain behaviour of clay is controlled by mineralogy, physicochemical interactions between adjacent clay particles, interparticle forces, and soil structure. Changes in pore fluid composition influence physicochemical interactions and alter the strength, compressibility and hydraulic conductivity of affected clays (Man and Graham, 2010). Patterson (2006) examined the effects of treating a range of soils with water of varying Sodium Adsorption Ratios (SAR) and noted that the loss of permeability (soil hydraulic conductivity) increased with increasing SAR and a small change in electrolyte concentrations. He also performed certain tests and reported that the various concentrations of particular soluble salts in effluent may affect the soil in different ways. For example, calcium induces flocculation while sodium favours dispersion of structural stability. The tremendous increase in human population and industrial activities exacerbates the problems of soil and groundwater contamination (Smith and Perdek, 2004). In many cases, the problem is noticed long after the aquifer is contaminated, when groundwater users have been exposed to health risks. Rapid growth of urbanization, industrialization as well as agricultural activities is causing groundwater contamination worldwide. The utilization of fertilizers, pesticides, disposal of solid wastes, and untreated waste water on land has further deteriorated groundwater quality (Singh et al., 2010). Groundwater contamination by nitrogen from animal feedlots, septic tank, and drain fields have been recorded in many instances. Nitrogen compounds can be oxidized to nitrate by soil bacteria and may be carried into the groundwater by percolating water. Once in the aquifer, nitrates move freely with the groundwater flow. Sources of groundwater contamination by nitrate can be classified into point and non-point sources. Non-point sources of nitrogen include fertilizers, manure application, leguminous crops, dissolved nitrogen in precipitation, irrigation return-flows, and dry deposition. Point sources such as septic systems and cesspits can also be major sources of nitrate pollution (Hajhamad and Almasri, 2009). It can cause methemoglobinemia (infant cyanosis, or blue baby disease) in infants who have been given water or fed formulas prepared with water having high nitrate concentration. A domestic water supply should not contain nitrate concentration in excess of 10mg/l (expressed as nitrogen). High levels found in shallow wells may be an indication of seepage from septic systems or livestock manure deposits (USEPA 2009). The influence of groundwater on the geotechnical properties of Nigerian soils has begun to receive some attention from various researchers. Not much work has been documented on the effect of contaminated groundwater on the stability of structures or hydraulic properties of soils in Nigeria. Jegede, 2000 and Abam et al, 2000 have looked into the failure of highway pavements induced by groundwater. Apart from these few workers no known documented information on both the physical and chemical effect of groundwater on the geotechnical properties of Nigerian soils have been recorded. At the case study site in Odi-Olowo street, Isikan, Akure, Nigeria where nitrate contamination has been reported due to septic tank effluent, several building foundations have undergone some degree of settlement as a result of construction emplaced in marshy or swampy (high groundwater table) environment.

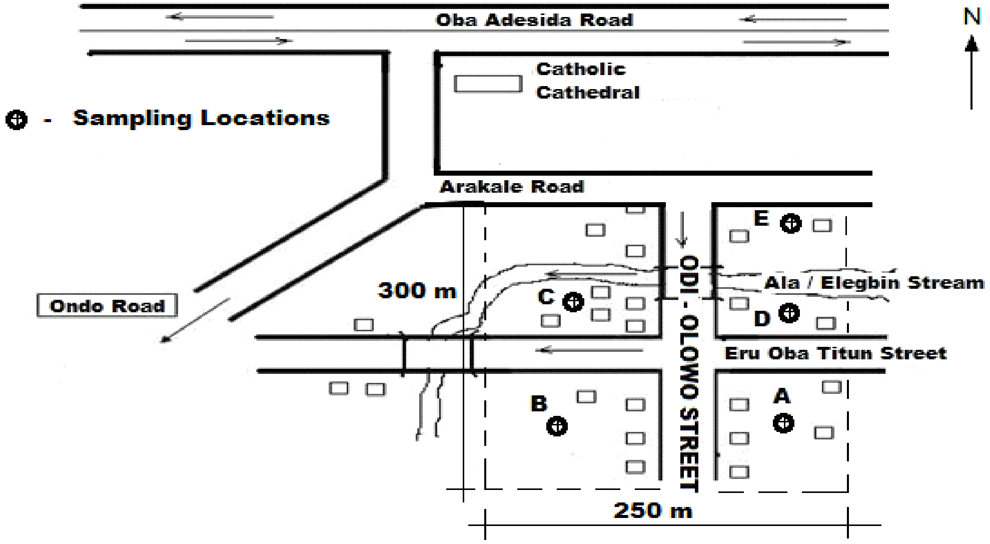
2. Materials and Methods

2.1. Site Reconnaissance

The case study site is Danjuma area, Odi-olowo Street, Isinkan, Akure, Ondo State, Nigeria. Akure is within the tropical climatic zone. The mean annual rainfall ranges between 1000 and 2000 mm and falls over more than 9 months of the year. The normal established rainfall periods are from March to July and September to October while August is usually dry (Balogun et al 2012). Isinkan is a suburban community located along Ondo road and also accessible from Arakale road, Akure. The study area lies within longitudes $5^0 10'$E and $5^0 22'$E and latitudes $7^0 20'$N and $7^0 30'$N in the south-western part of Nigeria. Isinkan comprise of several streets among which is Odi-olowo Street. Odi-olowo street (Figure1), having houses on both sides, is crossed by Eru Oba Titun Street and Ala/Elegbin stream.

Old Building structures along the stream have settled, such that most of them have been deserted. Observation of some wells around this area shows that the depth to water table is shallow, especially during the rainy season. People living within this area source their drinking water from wells. Interaction with some of the residents shows that this area experiences occasional flooding. The site is 300 meters by 250 meters in area has basin topography.

Figure 1: Site layout for the marshy area, Odi-Olowo Street, Isikan, Akure, Ondo State (case study site).



2.2. Contamination Assessment

Groundwater samples collected from eight existing hand dug wells were analyzed for pH, nitrate, and nitrite. The tests were conducted at the Ondo State Water Corporation Laboratory in Akure. pH was measured using a portable water quality meter, while nitrate and nitrite were analysed using the spectrophotometer method in the laboratory. Table 1 shows the results of the chemical analysis and the distance of each of the sampled well from septic tank. Depth to groundwater table within the study area was 1.8 meters during the investigation period (dry season). The depth to water table is usually shallow during the rainy season.

2.3. Soil Sampling

Soil samples for subsurface profiling and compressibility tests were collected from locations A, B, C, D and E (Figure 1). After the topsoil/vegetative soil was excavated in the process of digging the observation pits, representative soil samples were collected at 0.6-1.0 m, 1.0-1.4 m and 1.4-1.8 m, and transported to the laboratory. An undisturbed block clay soil sample for consolidation test was collected at a depth of 1.5 meters from location E on the Northern side of the site. There was no indication of nitrate contamination at location E where the clay soil sample was obtained. Soil sampling was done during the dry season.

2.4. Laboratory Testing

Geotechnical laboratory testing for soil index properties and classification was undertaken on selected samples taken from the test pits and the results for the index properties are summarised in Table 2. Geotechnical laboratory tests were conducted according to BS 1377:1990 as follows; moisture contents (BS1377:1990 Part 2:3), Atterberg tests (BS1377:1990 Part 2:4 & 5), specific gravity (BS1377:1990 Part 4), density tests (BS1377:1990 Part 4:5), Particle Size Distribution (BS1377:1990 Part 2:9) and one-dimensional consolidation tests (BS1377:1990 Part 6).

2.5. Oedometer Tests

A consolidation- swell test was carried out on five undisturbed specimens of clay soil obtained from block sample collected from location E using the front loading oedometer. The rigid stainless steel sample ring (75.0 mm diameter and 20 mm height) was used to cut each specimen of clay soil directly from the undisturbed large block sample. This was then placed in the consolidation cell and a nominal seating load of 7 kPa was applied. The specimen was then inundated with liquid (deionized water and solution with various nitrate concentrations for the different experiments) under constant pressure. Inundating undisturbed clay specimens with (30 mg/l to 200 mg/l) potassium nitrate solutions at a total vertical pressure of 7 kPa in oedometer cells exposed the clay specimens to nitrate contamination course. When the dial gauge reading became stable, that is, swell deformation ceased, incremental loading of 50, 100, 200, 400, 800, and 1600 kPa were applied. Each load increment was maintained for at least 24 hours and until the end of primary consolidation. The swelling characteristics of the samples were observed by unloading the sample decreasingly from 1600 kPa to 50 kPa after the completion of the loading process. Specimen 1 was inundated with deionized water (zero nitrate level). Specimens 2, 3, 4, and 5 were inundated with potassium nitrate solution, 30, 60, 120 and 200mg/l respectively.

2.6. Preparation of Nitrate Solution

A nitrate salt (Potassium nitrate) was chosen for this research work. Potassium nitrate, KNO_3, is a type of salt which has long been used as an ingredient in explosives. It is an odourless, white crystalline powder. It has a specific gravity of 2.109, melting point of 334^{o}C and Boiling point of 400°C. Its solubility in water is 383 g/l at 25° C. In this investigation, potassium nitrate (KNO3) salt was used for preparing nitrate nitrogen ($N0_3$-N) solutions used for artificially contaminating the soil by inundation under a nominal load in the consolidation cell. Potassium nitrate was dried in an oven for 24 hours at 105° C. Bearing in mind the ratio of the molecular weight of nitrogen (N) to potassium nitrate (KNO_3) which is 0.138. The authors dissolved 0.217 g of KNO3 in 1000 mL deionized water to make 30 mg/l nitrate nitrogen solution, 0.434 g of KNO3 in 1000 mL deionized water to make 60 mg/l nitrate nitrogen solution, 0.868 g of KNO3 in 1000 mL deionized water to make 120 mg/l nitrate nitrogen solution and 1.448 g of KNO3 in 1000 mL deionized water to make 200 mg/l nitrate nitrogen solution.

3. Results and Discussion

3.1. Contamination Assessment and Soil Characterization Results

Groundwater samples collected from eight existing hand dug wells in Odi Olowo Street, Akure were analyzed for pH, nitrate, and nitrite. Septic tank impact on the groundwater quality is pronounced. Nitrate contamination up to 60 mg/l nitrate nitrogen (NO_3-N) was recorded in some of the sampled hand dug well in the study area. The site was also noted for refuse dumping in the past which contributed to the high nitrate level in the subsurface. Table 1 shows the results of the chemical analysis and the distance of each of the sampled well from septic tank. The pH ranged between 8.0 and 8.4 with an average of 8.3. A maximum concentration of Nitrate-Nitrogen of 60 mg/l was recorded in well 8 with a distance of 6.0 meters from septic tank. Nitrate contamination was not detected in wells sited 15 meters and beyond from septic tank. Maximum nitrite-nitrogen concentration was also observed in well 8.

Table 1: Results of Chemical Analysis for Well water

Well Number	pH	Nitrate (as N) mg/l	Nitrite (as N) Mg/l	Distance from Septic tank(m)
1	8.4	ND	0.2	20.0
2	8.4	ND	0.4	18.0

Table 1: Results of Chemical Analysis for Well water - continue

3	8.1	ND	0.35	15 .0
4	8.0	2.0	0.2	8.0
5	8.5	0.8	0.4	7.5
6	8.2	1.2	0.8	10.0
7	8.2	12	2.5	6.0
8	8.3	60	4.2	6.0

ND- Not detected

Summary of the index properties for the five soil sampling locations, A, B, C, D and E are presented in Table 2a and Table 2b. Soil samples for subsurface profiling were collected at 0.6-1.0 m, 1.0-1.4 m and 1.4-1.8 m depths, indicated as 0.8 m, 1.2 m, and 1.6 m on the table. The soils at this site consist of top soil and organic material from the surface up to 0.6 meters, clayey silt and some sand between the depths of 0.6 m and 1.4 m. This followed by silty clay from the depths of 1.4 m to 1.8 m.

Table 2a: Summarized characteristics of soils at the site (Basic properties)

LOCATION	DEPTH (m)	NATURAL MOISTURE CONTENT%	BULK DENSITY (Kg/m^3)	SPECIFIC GRAVITY
A	0.8	40.3	1865.0	2.65
A	1.2	52.2	1903.0	
A	1.6	59.1	1951.0	2.70
B	0.8	37.6	1855.0	2.60
B	1.2	38.3	1916.0	
B	1.6	49.1	1970.0	2.68
C	0.8	38.5	1874.0	2.63
C	1.2	47.6	1925.0	
C	1.6	53.0	1982.0	2.74
D	0.8	46.1	1862.0	2.64
D	1.2	54.0	1885.0	
D	1.6	55.6	1910.0	2.75
E	0.8	32.5	1846.0	2.62
E	1.2	34.9	1880.0	
E	1.6	43.8	1905.0	2.67

Table 2b: Summarized characteristics of soils at the site (Soil classification tests)

LOCATION	DEPTH (m)	ATTERBERG LIMITS (%)		SIEVE ANALYSIS % PASSING			AASHTO CLASSIFICATION CLASS	DESCRIPTION
		LL	PI	#8 2.36 mm	#36 0.425 mm	#200 0.075 mm		
A	0.8	35.0	7.4	74	53	36	A-4	**Clayey SILT**
A	1.2	32.5	6.2	91	71	59	A-4	**Clayey SILT**
A	1.6	53.4	17.2	81	63	56	A-7-6	Silty **CLAY**
B	0.8	52.2	15.6	63	29	19	A-2-7	Clayey gravelly **SAND**
B	1.2	39.5	9.4	68	33	25	A-2-4	Clayey gravelly **SAND**
B	1.6	56.0	23.0	94	83	74	A-7-6	Silty **CLAY**
C	0.8	46.5	23.3	61	24	18	A-2-7	Clayey gravelly **SAND**
C	1.2	29.0	12.3	88	48	41	A-6	Sandy **CLAY**
C	1.6	45.2	18.4	95	81	76	A-7-6	Silty **CLAY**
D	0.8	44.0	21.0	66	18	16	A-2-7	Clayey gravelly **SAND**

Table 2b: Summarized characteristics of soils at the site (Soil classification tests) - continue

D	1.2	38.0	7.1	80	48	39	A-4	Sandy **SILT**
D	1.6	35.8	12.9	88	70	62	A-6	Silty sandy **CLAY**
E	0.8	26.7	7.6	64	45	25	A-2-4	Clayey sandy **GRAVEL**
E	1.2	28.0	13.2	48	26	18	A-2-6	Clayey sandy **GRAVEL**
E	1.6	43.4	23.0	85	72	63	A-7-6	Silty **CLAY**

AASHTO –American Association of State Highway and Transportation Officials
LL – Liquid limit, PI – Plasticity Index

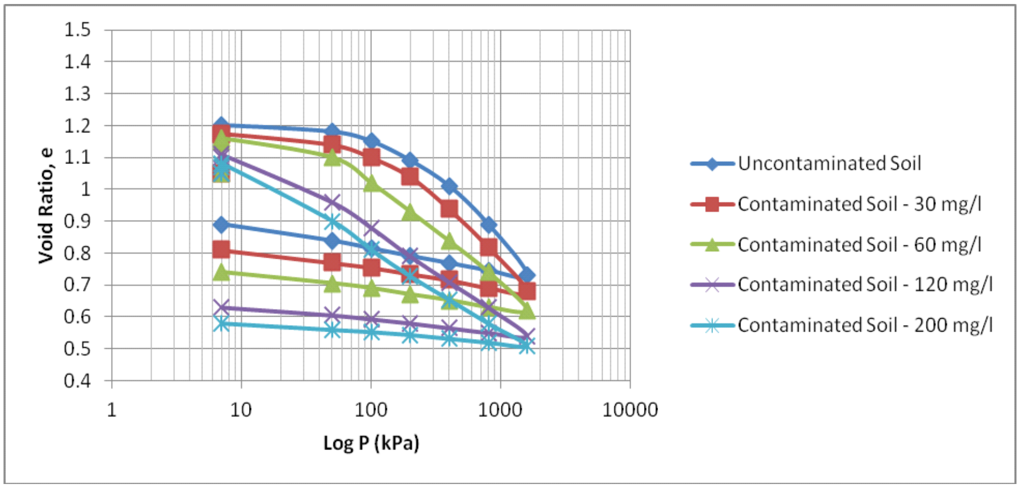
3.2. Swell-Consolidation Test Results

The results of the one dimensional swell-consolidation tests conducted on the uncontaminated soil sample and the contaminated soils at various degrees of contamination are summarized in Table 3. The compression indices of the samples were determined from the loading branch of the e-log P graph and the swell indices were determined from the unloading branch of the same graph (Figure 2). The coefficient of compressibility (a_v) was determined from the slope of the arithmetic plot of void ratio (e) versus pressure (P).The plot of dial readings versus square root of time was used to determine the coefficient of consolidation (c_v) using Taylor's curve fitting method (Das, 2002). The average coefficient of consolidation (c_v) over a stress increase range of 50 kPa to 1600 kPa is shown in Table 3.The coefficient of permeability (k) was determined for both uncontaminated and contaminated soil using equations (1) and (2).

Table 3: Tropical clay compressibility and permeability parameters at different degrees of nitrate contamination

Sample No.	**Level of Nitrate Contamination (NO_3-N) (mg/l)**	**Cv (cm^2/sec) x 10^{-4}**	**C_c**	**C_s**	**a_v (m^2/KN) x 10^{-4}**	**k (m/s) x 10^{-11}**
1	0	6.04	0.46	0.063	2.31	6.83
2	30	8.12	0.43	0.060	2.16	8.53
3	60	12.62	0.36	0.053	1.81	9.54
4	120	15.91	0.28	0.041	1.41	10.94
5	200	18.86	0.24	0.037	1.20	11.03

Figure 2: Plot of Void ratio Vs. Log P for the five samples



$$k = c_v \times m_v \times \gamma_w \qquad (1)$$

where;

k – coefficient of permeability

c_v – coefficient of consolidation

m_v – coefficient of volume compressibility

γ_w – unit weight of water

$$m_v = \frac{a_v}{1+e_o} \qquad (2)$$

where;

a_v – coefficient of compressibility

e_o – initial void ratio

3.3. Correlation of Swell-Consolidation Parameters with Degree of Nitrate Contamination

The plots of the compressibility and permeability parameters against degree of nitrate contamination and compressibility and permeability parameters with a linear and polynomial trend lines are shown in Figure 3a&b to Figure 6a&b.

Figure 3a: Relationship between Compression index [C_c] and Nitrate concentration [NO_3-N] (Linear)

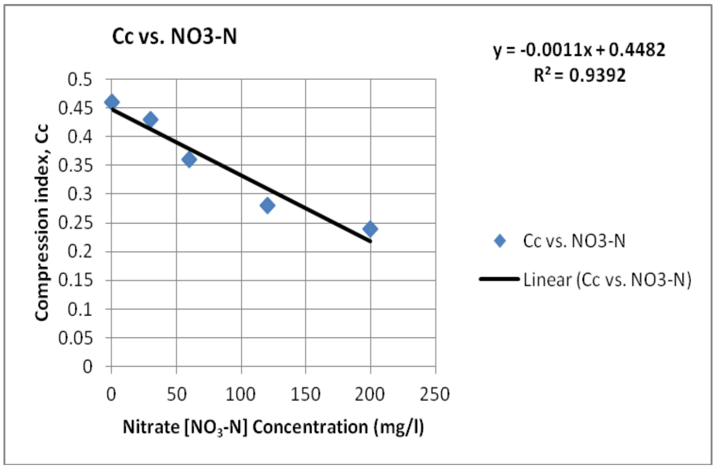


Figure 3b: Relationship between Compression index [C_c] and Nitrate concentration [NO_3-N] (Polynomial)

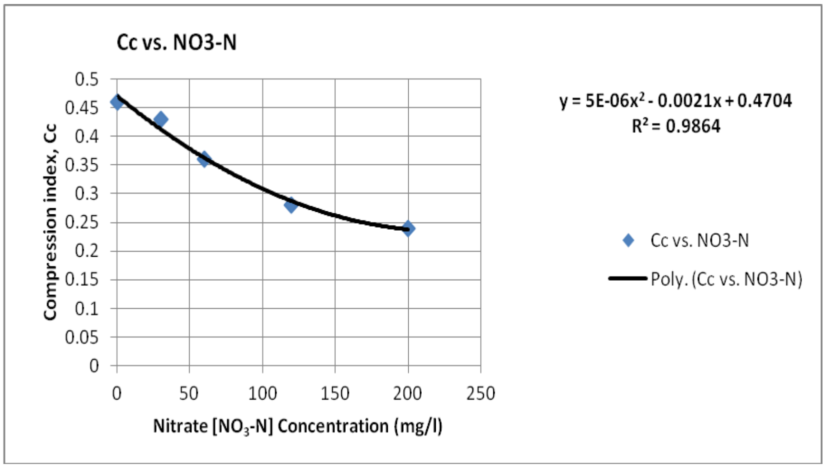


Figure 4a: Relationship between Swell index [C_s] and Nitrate concentration [NO_3-N] (Linear)

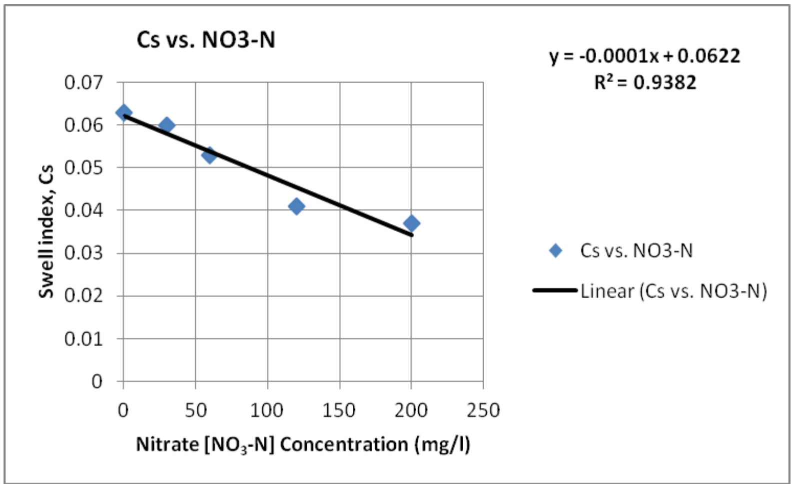


Figure 4b: Relationship between Swell index [C_s] and Nitrate concentration [NO_3-N] (Polynomial)

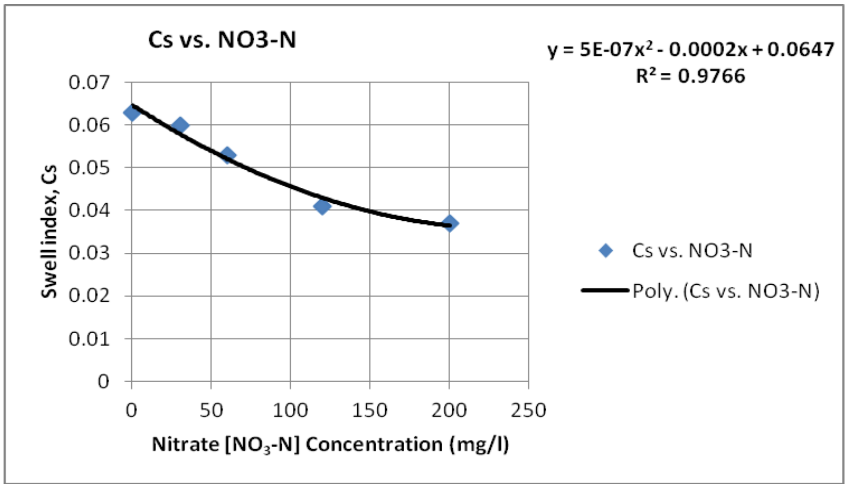


Figure 5a: Relationship between Coefficient of consolidation [$_{Cv}$] and Nitrate concentration [NO_3-N] (Linear)

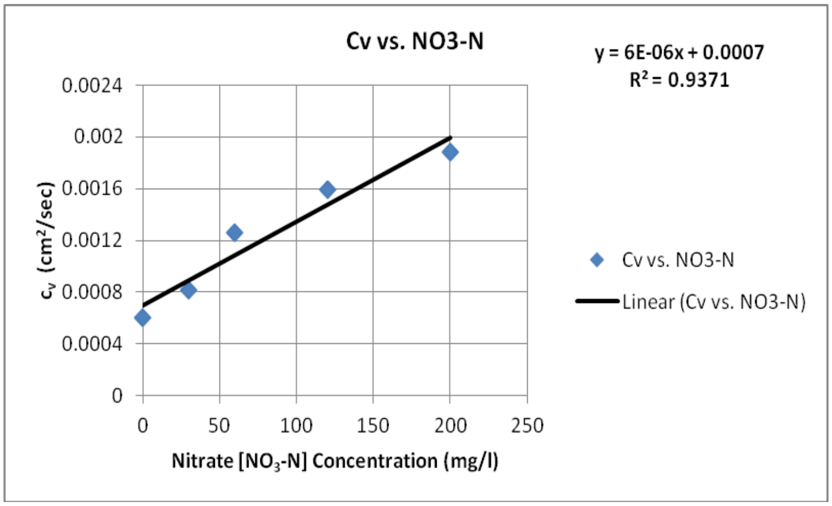


Figure 5b: Relationship between Coefficient of consolidation [$_{Cv}$] and Nitrate concentration [NO_3-N] (Polynomial)

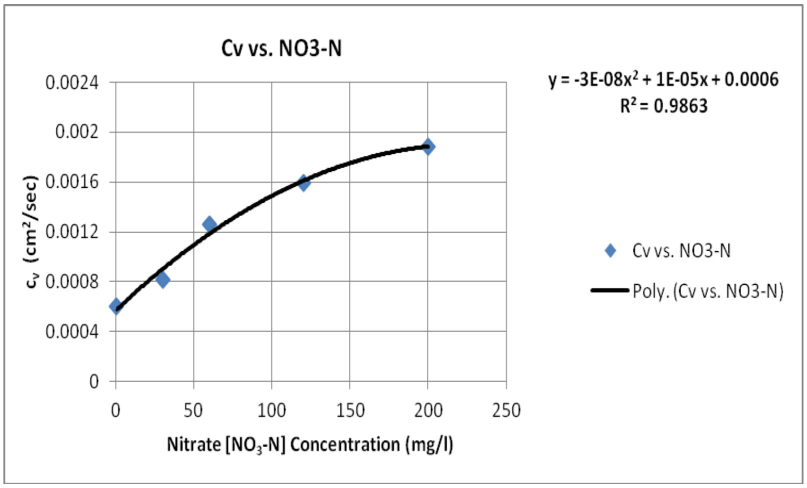


Figure 6a: Relationship between Coefficient of permeability [k] and Nitrate concentration [NO_3-N] (Linear)

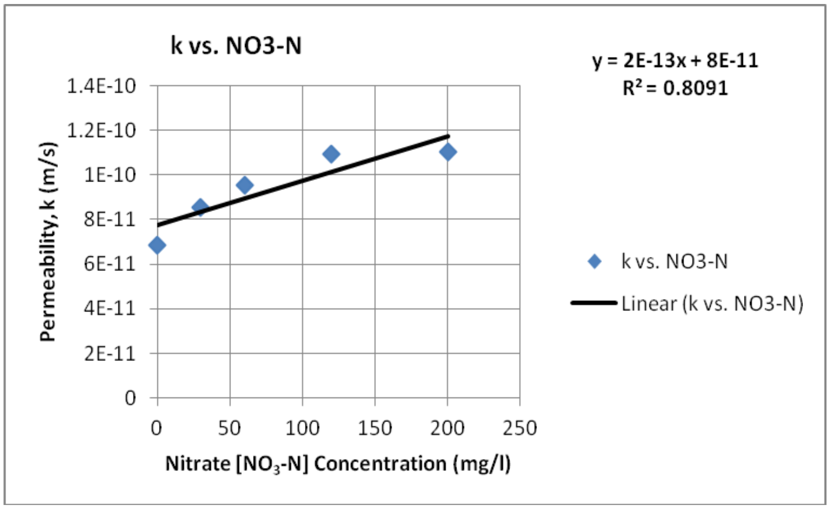
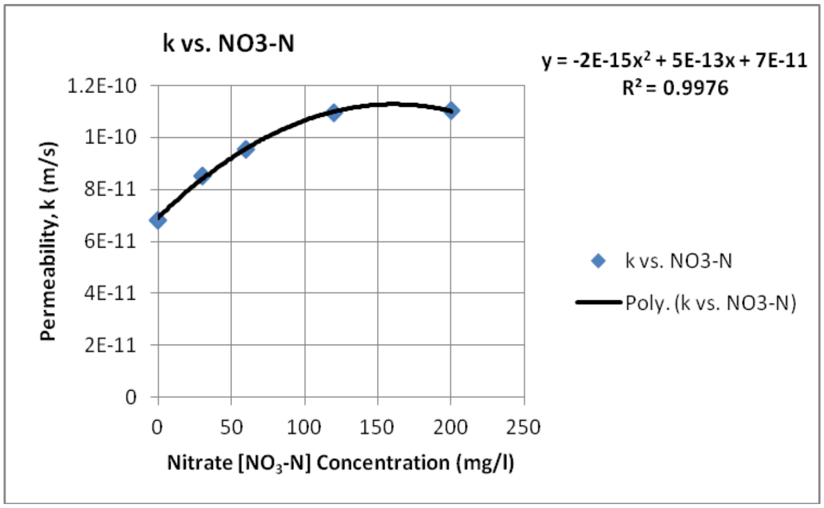


Figure 6b: Relationship between Coefficient of permeability [k] and Nitrate concentration [NO_3-N] (Polynomial)



The quantity “R^2” called coefficient of determination is an index of correlation between the two variables and varies between zero and one. It is always non-negative and it is the square of the coefficient of correlation “R” which lies between –1 and +1. From the coefficient of determination for the plot of compression index ‘c_c” versus Nitrate concentration [NO_3-N] Figure 3b, the polynomial relation;

$$C_c = \left(5\times10^{-6}\right)\left[NO_3N\right]^2 - 0.0021\left[NO_3N\right] + 0.4704 ....(R^2 = 0.9864) \qquad (3)$$

gives the best equation relating compression index to degree of nitrate contamination for the tropical clayey soil under investigation. From the results, it is obvious that the pattern of change in the compression index “c_c” and coefficient of compressibility “a_v” with degree of nitrate contamination are similar. Generally the compression index and coefficient of compressibility decrease with increase in degree of nitrate contamination.

The polynomial relation;

$$C_s = \left(5\times10^{-7}\right)\left[NO_3N\right]^2 - 0.0002\left[NO_3N\right] + 0.0647 ....(R^2 = 0.9766) \qquad (4)$$

gives the best equation relating swell index to degree of nitrate contamination (Figure 4b).

The coefficient of consolidation “c_v” generally increases with increasing degree of nitrate contamination (Figure 5). The polynomial graph Figure 5b has given the best relationship with coefficient of determination R^2 = 0.9863 and the relation;

$$c_v = \left(-3\times10^{-8}\right)\left[NO_3N\right]^2 + \left(1\times10^{-5}\right)\left[NO_3N\right] + 0.0006 ....(R^2 = 0.9863) \qquad (5)$$

The coefficient of permeability “k” also increased with increasing degree of nitrate contamination (Figure 6). The polynomial graph Figure 6b has given the best relationship with coefficient of determination R^2 = 0.9976 and the relation;

$$k = \left(-2\times10^{-15}\right)\left[NO_3N\right]^2 + \left(5\times10^{-13}\right)\left[NO_3N\right] + \left(7\times10^{-11}\right) ....(R^2 = 0.9976) \qquad (6)$$

Equation 4 relating coefficient of permeability “k” with degree of nitrate contamination gave the highest correlation index $(R^2 = 0.9976)$. Increase in nitrate contamination for the clayey soil studied affected the microstructure of the clay resulting in flocculated structure. The repulsion forces between particles were reduced and the electrically attracted water that surrounds each clay particle was decreased causing more open channels for free water flow. This has led to a decreased compressibility and increased permeability of the soil.

The lack of chemical analysis for soil and groundwater in a contamination prone area before construction can lead to an overestimation of the swell and compressibility indices for the site. It has therefore been recommended amongst other things that proper chemical analysis of soil and groundwater be done prior to construction, especially when the soil is suspected to have been exposed to groundwater contaminants and where the water table is found to be high.

4. Conclusions

The compression index, swell index and coefficient of compressibility (C_c, C_s and a_v) decreased with increase in degree of nitrate contamination. The coefficient of consolidation “c_v” and coefficient of permeability “k” generally increased with increasing degree of nitrate contamination. This implies that the swell potential, magnitude and rate of settlement are affected. These properties directly influence the performance of shallow structural foundations. Permeability of the clayey soil increased significantly with increase in nitrate contamination, this portends the danger of emerging breakthrough of contaminants in the shallow contaminated zone through the underlying clayey layer to deeper confined aquifers being relied upon through water supply borehole exploitation for portable drinking water.

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